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Digital Mapping, Charting, and Geodesy Analysis Program (DMAP)

Spatial and Temporal Reference Systems and the 4D3 Concept

HILLARY MESICK
SUSAN CARTER
MICHAEL HARRIS

Mapping, Charting, and Geodesy Branch
Marine Geosciences Division

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Hillary Mesick, Susan Carter, and Michael Harris

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14. ABSTRACT
A technical review of the Spatial and Temporal Reference Systems and the 4D3 Concept was performed by the Digital Mapping, Charting, and Geodesy Analysis Program (DMAP). Background, discussion points, and conclusions are presented.

15. SUBJECT TERMS
Spatial and Temporal Reference Systems; 4D3 Concept

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Spatial and Temporal Reference Systems and the 4D3 Concept

Background

In keeping with the "Four Dimensional Cubed" (4D3) Concept, a uniform spatio-temporal reference system for the effective coordination of joint warfighter activities is required. A brief examination of several important concepts, NIMA products, and other items of interest are examined in their relationship to 4D3.

Spatial Reference

In order for all warfighters to work together in an effective and coordinated manner it is a necessity that all parties occupy the same conceptual framework during the decision making process. One element of this framework is a common view of the battle space geometry, both in position and time. Toward this end the World Geodetic System 1984, (WGS84) ellipsoid and Universal Coordinated Time (UTC) as distributed by the GPS are selected to provide the common reference system.

WGS84

At cartographic scales and positional accuracy of interest to the warfighter the earth cannot be assumed to be a regular sphere of constant radius. In fact, the earth is a rather irregular spherical glob that bulges somewhat at the equator. The actual shape of the earth, at large scales, is not that well known; and to the degree that it is presently known the description is mathematically intractable. In dealing with this situation Geodesists have developed a mathematically describable surface or model that is a "best" fit to the actual shape of the earth when the earth's figure is described as an equi-potential gravitational surface situated at mean sea level, the Geoid. Thus, in general WGS-84 defines a **mathematical surface**, an oblate ellipsoid of revolution with the axis of revolution collinear with the polar spin axis of the poles. (Since the polar spin axis wanders slightly a standard geographical location is chosen). The defining parameters for WGS-84 are an equatorial radius (a) **or semi-major axis** of **6,378,137.0 meters** and **flattening** (f) of **1/298.257223563**. Flattening (f) is defined as 1 – (b/a) where b is the semi-minor axis of the ellipse and a semi-major axis. As additional geodetic data becomes available the defining parameters of WGS-84 periodically undergo very small changes. The effects of these changes are on the order of five or so centimeters in positional adjustment, having little or no effect on practical navigation usage.

Horizontal Datum

A horizontal datum defines the method of giving locations to point on the earth with respect to an assumed starting location and measurement method. WGS-84 employs latitude and longitude measured in a conventional sense from a well-defined origin.

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However in the case of WGS-84 latitude and longitude, the position of a point on the earth is defined by a line normal to the mathematical surface of the ellipsoid and intersecting the earths surface at that location. **Latitude and longitude by themselves in WGS-84 refer to a location on the surface of the ellipsoid and not on the earth's surface**. In general the local vertical as determined by gravity will be slightly different from the ellipsoid normal, resulting in astronomically determined positions differing from WGS-84 positioning by a nominal amount.

Vertical Datum

In addition to the latitude and longitude of a point, an elevation is also required if the location of a point is to be fully specified. An elevation determined by WGS-84 is the distance of the point from the ellipsoid as measured along a normal to the ellipsoidal surface. Notice, this distance is not a measured from mean sea level nor is it the height above the ground.

Geoid

The Geoid is defined as an equal gravitational potential surface about the earth that corresponds closely with mean sea level. If the earth was covered with water and the surface corresponded to this equi-potential gravitational surface there would be no tendency for the water to flow between any two points; i.e., the surface is "level" and the gravitational field vector is normal to the surface at every point. The Geoid does not correspond to the earths topographic or sea surface in general, due to variations in the distribution of mass within the body of the earth. But unlike an ellipsoid it is a physical surface and not a mathematical model.

Geoid Model / Ellisoid - Geoid Separation

The Geoid, while a surface determined by gravitational potential, is not known precisely at all points on the earth, due to insufficient data. (The earth is a big place). To address this issue all the available data from gravity measurements and satellite orbits were used to compute an estimate of the Geoid. By use of this model one can calculate for any given location the "height" of the Geoid relative to the earth's mass center. Since the Geoid height and mean sea level correspond we can then calculate the height of mean sea level above earth mass center.

The Geoid is a complex surface with dimples and bumps, unlike that of the WGS-84 ellipsoid, which is smooth. One could think of the Geoid as being more "natural" and the ellipsoid as more "abstract". The increased abstraction and resulting simplification through the use of an ellipsoid is necessitated by mathematical expediency.

At this point we have two earth mass centered heights, Geoid height and WGS-84 height. Given a GPS determined WGS-84 height and if we know the distance separating the Geoid height and the WGS-84 height, we could calculate the height of the GPS receiver in terms of mean sea level or other vertical datums that are reference to the Geoid. This

difference in height between the Geoid and the ellipsoid is termed the Geoid/Ellisoid separation, and the numerical sign convention is such that the elevation, also termed the **orthometric height**, of a point is given by **H = h – N**, where **h is WGS-84** height and **N is Geoid separation**. Thus by subtracting the geoid separation from the GPS determined height we obtain the elevation of the GPS in terms more closely related to values that one would find on a map or chart.

In the days of Mathew Maury, the first Oceanographer of the Navy, prior to GPS and modern gravitometers the basis of elevation determination or the vertical datum was mean sea level. Mean sea level is determined with a tide gauge, many measurements, and 18.6 years of observations. Once the mean sea level (MSL) had been determined at a tide observation station and benchmarks set, elevations were then run along coastal regions by mean of differential leveling (bubble-level telescopes) and additional reference bench marks set at other harbors and points inland.

Eventually a network of tidal stations was developed and a uniform best-fit datum established to all the tidal stations. This system over the years has undergone successive refinement: National Geodetic Vertical Datum of 1929 and North American Vertical Datum of 1988. Other countries have undergone similar development in their establishment of vertical reference systems.

MSL / MLLW / Ellipsoid Height

Historically nautical charts in coastal areas have used Mean Low Low Water (MLLW) as the vertical datum for bathymetric soundings. The reasoning behind this is that a sailor could be guaranteed to have the charted amount of water beneath his keel regardless of the status of the tidal cycle at the time, in fact most of the time the water depth would be greater than the charted depth (a built-in safety factor). This datum is established by means of tidal gauge observation, numerical tidal modeling and is intimately related to the tidal dynamics of the charted area. **The Geoid is directly correlated to mean sea level, however its relationship to MLLW is much more complex, being strongly influenced by the tidal basin geometry and orientation.** This represents a problem if one would like to express the bathymetry in terms of WGS-84 ellipsoid height. In order to convert from MLLW to WGS-84 vertical datum, one needs to know the WGS-84 elevation of the MLLW datum. If this factor is known then a simple arithmetic conversion is all that is required. However, it may frequently be the case, that for older charts (prior to extensive use of GPS) these correction factors maybe unknown. But for many of these older charts the MLLW datum can be related to MSL or other national vertical datums and ellipsoids and the appropriate correction factors derived. Where these historical facts are no longer available, the use of global geoid models in conjunction with tidal models may suffice to produce the correct offset value to the required accuracy level. This will require that each nautical chart have sufficient meta-data to permit the referencing of the MLLW datum used for the chart to a another vertical datum related to WGS-84 elevations (ellipsoid height).

It should be keep in mind that when a nautical chart is "updated" to show depth with reference to the WGS-84 ellipsoid, tidal data must be made available to the user so that actual depth under the keel can be anticipated for the portion of the tidal cycle during the time of planned or actual operations.

Aircraft

The majority of aircraft use barometric altimeters for altitude determination. Below 19,000 feet aircraft set their altimeter to the standardized barometric pressure at nearest reporting airfield or flight service station. Under this situation, all altimeters would read field elevation on the runway of the reporting airfield. This elevation is reference to MSL but can differ from WGS-84 ellipsoid heights. Above 19,000 feet all aircraft set their altimeter to 29.92" of mercury regardless of the standardized pressure in the flight area. While this causes increased error in absolute elevation determination, it does keep all aircraft on the "same page" when in relative proximity. Flying at high speeds makes it impractical to continually adjust the altimeter to nearest reporting airfield. So, while reducing absolute accuracy in elevation it does make for a more regulated air traffic control. With more aircraft becoming GPS equipped barometric altimeter usage may be on the wane. However it should be kept in mind that the two elevations, barometric and GPS (WGS-84) are not the same, and that at some levels of required accuracy the difference will be significant.

High performance aircraft when operating at high speeds and maneuver rates may exceed the ability or computational speed of the GPS equipment to accurately derive position.

NIMA Products

A brief survey of NIMA digital product specifications was conducted. The result of this survey with respect to horizontal and vertical datums is presented in the table that follows:

Product[1]	**Reference Specification / Date**	**Horizontal Datum**	**Vertical Datum**
CIB	MIL-PRF-89041 15 May 95	World Geodetic System (WGS 84)	World Geodetic System (WGS 84)
DNC	MIL-PRF-89023 19 Dec 97	World Geodetic System (WGS 84)	Shoreline features – Mean High Water Topographic features – Mean Sea Level Hydrographic features – low water tide level

[1] See Attachment A for List of NIMA Acronyms.

Product[1]	Reference Specification / Date	Horizontal Datum	Vertical Datum
DPPDB	MIL-PRF-89034 23 Mar 99	World Geodetic System (WGS 84)	World Geodetic System (WGS 84)
DTED (00-Present)	MIL-PRF-89020B 23 May 00	World Geodetic System (WGS 84)	Mean Sea Level (MSL) as determined by the Earth Gravitational Model (EGM) 1996
DTED (96 – 00)	MIL-PRF-89020A 14 Apr 96	World Geodetic System (WGS 84)	Mean Sea Level (MSL)
DTOP	MIL-PRF-0089037 14 Nov 98	World Geodetic System (WGS 84)	Mean Sea Level (MSL)
FFD	MIL-PRF-89049-1 30 Nov 98 (Draft)	World Geodetic System (WGS 84)	Mean Sea Level (MSL)
LWD	MIL-PRF-89049-7 18 May 98	World Geodetic System (WGS 84)	Standard Vertical Datum (WGS-84 Ellipsoid)
TOD0	MIL-PRF-89049/10 24 Nov 98	World Geodetic System (WGS 84)	Low water tide level
TOD1	MIL-PRF-89049/11A 16 July 99	World Geodetic System (WGS 84)	Mean Sea Level (MSL)
TOD2	MIL-PRF-89049/12A 16 July 99	World Geodetic System (WGS 84)	Mean Sea Level (MSL)
TOD4	MIL-PRF-89049/14 15 Mar 00	World Geodetic System (WGS 84)	Mean Sea Level (MSL)
VMAP0	MIL-V-89039 9 Feb 95	World Geodetic System (WGS 84)	Mean Sea Level (MSL)
VMAP1	MIL-PRF-89033 1 June 95	World Geodetic System (WGS 84)	Mean Sea Level (MSL)
VVOD	MIL-PRF-89049/9 4 Dec 97	World Geodetic System (WGS 84)	Mean Sea Level (MSL)
WVS Plus	MIL-PRF-89012A 24 Aug 99	World Geodetic System (WGS 84)	Shoreline – Mean High Water Hydrographic – Mean Sea Level

Time

Time

Within the context of 4D3 time is a much simpler issue than vertical datum in concept, but may present more difficulty in its full implementation. Accurate and uniform time is globally available with GPS. All commonly available GPS units supply time, UTC, to the user at one-second intervals. More sophisticated units are capable of more frequent updates. While the "time" is accurate to milliseconds, delays in digital propagation and storage buffering may cause a delay in the observed time associated with other data as it is recorded. That is, there could be processing latency as the GPS time comes into association with other real-time measured data during storage or retransmission.

Traditionally, time information while available, frequently was not stored explicitly with environmental data due to the increase in storage capacity required. Usually, sufficient information was available to compute the collection time if required. The 4D3 concept places more emphasis on an implicit association of time and position, so that time and position information remain tightly coupled throughout their transmission and storage.

Accuracy

The 4D3 concept should also be linked to definitive levels of accuracy. As an example Class A might specify 1 meter positioning accuracy and 1 second temporal accuracy, Class B 10 meters ... and so forth. All measurements have accuracy limitations. It is important that as data is employed by users other than the originator, that the limits of data accuracy remain available to the "down-stream" user.

Compliance

The Oceanographer of the Navy has placed emphasis on the 4D3 concept as an integral component of effective Network Centric Warfare.[2] All current and future systems should be reviewed to verify the use of WGS-84 positioning and GPS derived UTC as essential elements of data collection, logging and transmittal.

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[2] R.D. West; Oceanographer of the Navy *Naval Oceanography Program Operational Concept, Mar 02; Ref: Correspondence Department of Navy 3150 Ser N096/2U570471*

Conclusions

- WGS-84 and GPS provide a good framework for the implementation 4D3.

- All current and future systems should be reviewed to verify the use of WGS-84 positioning and GPS derived UTC.

- The problem of the integration of tidal datums with the WGS-84 datum must be addressed.

- Tidal information must be provided to the user of a "WGS-84 Bathymetric Chart" in an effective manner.

- More attention must be devoted to tightly coupling time and position in all data handling.

- Standardized accuracy levels should be established early in the process of 4D3 implementation.

Additional References

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Appendix A
List of NIMA Acronyms

CIB	Controlled Image Base
DNC	Digital Nautical Chart
DPPDB	Digital Point Positioning Database
DTED	Digital Terrain Elevation Data
DTOP	Digital Topographic Data
FFD	Foundation Feature Data
LWD	Littoral Warfare Data
TOD	Tactical Ocean Data
VMAP	Vector Map
VVOD	Vector Vertical Obstruction Data
WVS Plus	World Vector Shoreline Plus